

Electromagnetic interactions at RHIC and LHC

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Abstract

At LHC energies the Lorentz factor will be 3400 for the Pb + Pb collisions and the electromagnetic interactions will play important roles. Cross sections for the electromagnetic particle productions are very large and can not be ignored for the lifetimes of the beams and background. In this article, we are going to study some of the electromagnetic processes at RHIC and LHC and show the cross section calculations of the electron-positron pair production with the giant dipole resonance of the ions.

1 Introduction

For the LHC and RHIC energies, cross section of the lepton pair production is very large for the Pb + Pb and Au + Au collisions. In this work, we focus mainly on ultra-peripheral collisions (UPC) of heavy ions for $b > 2R$ region. In this type of collisions, purely electromagnetic interactions and photo-nuclear interactions are the dominant processes [1, 2]. Production of free e^+e^- pairs and bound-free production of e^+e^- pairs play important roles at RHIC and at LHC. Free electron-positron pair production cross sections are about 36 kbarn at RHIC energies (Au+Au collisions) and about 227 kbarn at LHC energies (Pb+Pb collisions). On the other hand bound-free pair production cross sections are about 80 barns at RHIC energies and about 200 barns at LHC energies for the corresponding ion collisions. Therefore it is an important contribution to the background and with the electromagnetic excitation of the giant dipole resonance play important role for limitation to the lifetime of the beams. All these electromagnetic processes result in a change in the charge of the ions in the beams.

In Table 1. we have tabulated the parameters for accelerators SPS, RHIC and LHC. E_{crit} is the critical electric field, and E_{max} is the maximum electric field to produce electron-positron pairs. As we clearly see that for higher energies the ratio of maximum electric field to critical electric field is become larger.

There are many attempts to calculate electromagnetic lepton pair production cross section. The two-photon process [3, 5, 6, 4] has been modeled through the equivalent-photon approximation. In this model, the equivalent-photon flux associated with a relativistic charged particle is obtained via a Fourier decomposition of the electromagnetic interaction. Cross sections are obtained by folding the elementary, real two-photon cross section for the pair production process with the equivalent-photon flux produced by each ion. Although the results for the total cross sections are reasonably accurate, however, the details of the differential cross sections, spectra, and impact-parameter dependence differ. The method loses applicability at impact parameters less than the Compton wavelength of the lepton, which is the region of greatest interest for the study of nonperturbative effects.

Table 1: Integrated cross sections for Au-Au collisions at RHIC energies for STAR experimental restrictions. First row shows the calculations of Hencken et al. Second row is obtained by Monte Carlo QED calculation and third row shows the same calculation with Woods-Saxon nuclear form-factor.

Parameters	SPS	RHIC	LHC
γ	10	100	3400
$E_{max}(\text{V/m})$	10^{20}	10^{22}	10^{26}
E_{max}/E_{crit}	1.6	160	54,000

Most of the calculations show that cross sections of free pairs production agree with the following equation

$$\sigma_{free\ pairs} \sim Z_1^2 Z_2^2 \ln(\gamma)^3. \quad (1)$$

where Z_1 and Z_2 are the charge numbers of the target and projectile nuclei, and γ is the Lorentz factor. We have also calculated free lepton pair production numerically by using the Monte-Carlo techniques and found out that our results agree with the above equation. Free pair production cross section is proportional to the energy and square of the charges of the colliding nuclei.

When an electron-positron pair is produced, one of the electron can be bound to one of the incident nuclei. This electromagnetic processes is called bound-free pair production (it is shown in figure 1.) and the cross section is about 280 b for Pb + Pb collisions at LHC and is about 80 b for Au + Au collisions at RHIC energies. The bound-free pair production cross section plays important roles for the monitoring luminosity of the heavy-ion beams at the LHC. There are many different calculations for capture into a K-shell orbit,

$$\sigma_{capture} \sim Z_1^5 Z_2^2 \ln\left(\frac{\gamma}{\Delta}\right). \quad (2)$$

where Z_1 is the charge number of the ion capturing electron, and Δ is a slowly varying parameter. Recent report [7] shows the first measurement of the beam losses due to electron capture at RHIC. 100 GeV/nucleon $^{63}\text{Cu}^{29+}$ ions are used at RHIC, and the measurement confirms the order of magnitude of the theoretical calculations.

We have obtained cross section expressions for electron-positron pair production from relativistic heavy ion collision based on a lowest order QED calculation. Our Lagrangian consists of three terms:

$$\begin{aligned} \mathcal{L}_{QED} &= \mathcal{L}_{e^+e^-} + \mathcal{L}_{EM} + \mathcal{L}_{int} \\ &= \bar{\Psi}(i\hat{\partial} - m_e)\Psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - e\bar{\Psi}\gamma^\mu\Psi A_\mu \end{aligned} \quad (3)$$

Here $\mathcal{L}_{e^+e^-}$ is the term for the free electrons-positrons, \mathcal{L}_{EM} is the electromagnetic field and \mathcal{L}_{int} is the interaction term between the leptons. At RHIC and LHC energies, for small impact parameters pair production probabilities violates the unitarity. Therefore lowest order diagrams do not describe the pair production process and higher order terms must be included

Because of the some technical difficulties, we have not fully tested the theoretical calculations and experimental results of electron-positron pair production. Vane et al. [8] has obtained experimental data at SPS for lepton pair production. In comparison with data, we find that the two-photon external-field model does quite well for the region where a majority of the pairs are being produced. However, for the high-energy (or high-momentum) tail, the theory is under predicting the data.

In this work, we calculate the probability of electron-positron pair production in lowest order QED. We use semi-classical approximation in the calculation and use Monte Carlo method to obtain exact results. We then compare our results with the STAR Collaboration and other theoretical calculations.

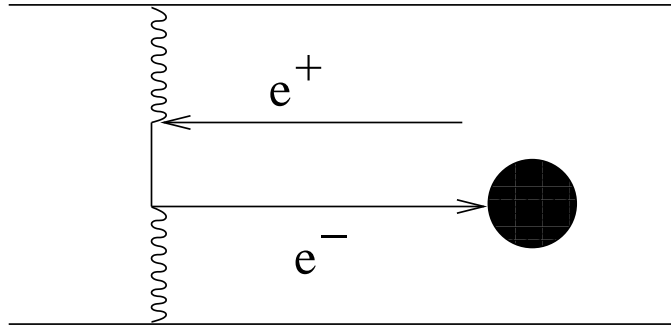


Figure 1: Diagram for pair production with capture (bound-free pair production) in relativistic heavy-ion collision.

2 Calculation of $e^- e^+$ pair production with giant dipole resonance

Recently, the STAR Collaboration has measured electron-positron pairs together with the electromagnetic excitation of both ions, predominantly to the giant dipole resonance. In such measurement, it is assumed that no hadronic interactions occur and minimum impact parameter is twice the nuclear radius. The STAR Collaboration used Gold atoms at $\sqrt{s_{NN}} = 200$ GeV per nucleon energies. The decay of the excited nucleus generally emits one or two neutrons and these neutrons are detected in the forward Zero Degree Calorimeter (ZDC).

The STAR detector measures the produced electron-positron pairs for the limited kinematic range of pair mass $140 \text{ MeV} < M_{ee} < 265 \text{ MeV}$, pair rapidity $|Y| < 1.15$ and the transverse momentum $p_{\perp} > 65 \text{ MeV}$. If the pair production is independent of the nuclear excitation, the total cross section of electron-positron pair production with Giant Dipole Resonance can be written as

$$\sigma_{e^-e^+}^{GDR} = 2\pi \int_{\rho_{min}}^{\infty} d\rho \rho P_{e^-e^+}(\rho) P_{GDR}^2(\rho) \quad (4)$$

where $P_{e^-e^+}$ is the probability of electron-positron pair production and $P_{GDR}(b)$ is the probability of a simultaneous nuclear excitation as a function of impact parameter.

Previously, we have calculated lepton-pair production by using the lowest order Feynman diagrams. According to this QED calculation we have obtained the total pair cross section as

$$P_{e^-e^+}(\rho) = \frac{1}{2\pi\rho} \frac{d\sigma}{d\rho} = \frac{1}{2\pi} \sigma_T \frac{\rho_0}{(\rho_0^2 + \rho^2)^{3/2}} \quad (5)$$

here σ_T is the total cross section of free lepton pair production cross section and it is equal to $\sigma_T = Z_1^2 Z_2^2 \ln(\gamma)^3$ and ρ_0 is the parameter that is obtained numerically. We have calculated the above function for Au + Au collisions for $\gamma = 10, 100$ and 3400 . This particular calculations show that for a fixed values of one variable in the equation is in exponential form. By examining the fluctuations between the points for different values of a fixed variable, and from standard estimates for the errors of a Monte Carlo integration, we take sufficient points until we believe that each points has converged to within five percent. A smooth function is then fit to the calculated numbers.

We have determined the constants ρ_0 at RHIC energies for STAR parameters and without any restrictions. It is equal to $1.35\lambda_C$ without any restrictions and $0.114\lambda_C$ for the STAR kinematic restrictions. When we integrate this impact parameter dependence cross section over the impact parameter,

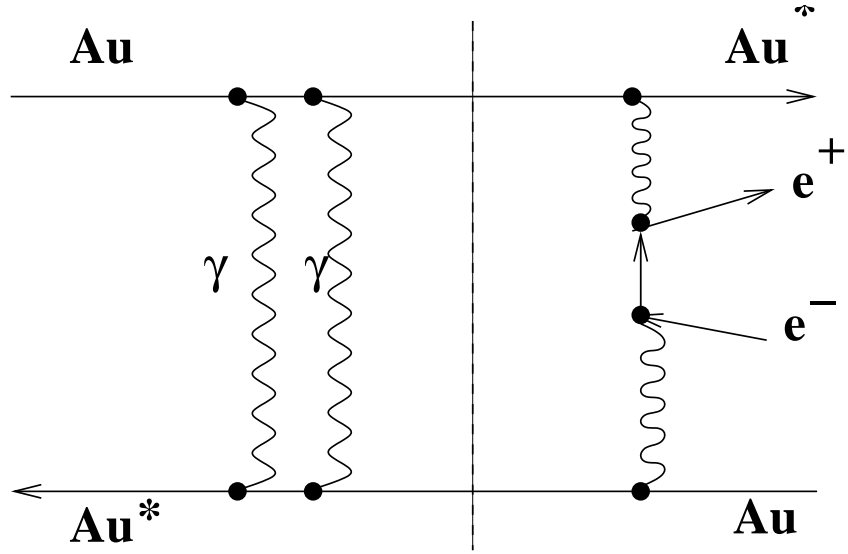


Figure 2: Electron-positron production (on the right) with a mutual Coulomb excitation (on the left) mainly giant dipole resonance (GDR). These two processes are independent from each other.

we obtain the total cross section, and the parameter ρ_0 is disappear in the total cross section. In this calculation, there is no kinematic restriction for pair mass, rapidity and transverse momentum. In order to compare with the STAR experiment, we also restrict the pair rapidity $|Y| < 1.15$ and the transverse momentum $p_\perp > 65$ MeV. The total untagged cross section is 0.322 barn and it is in perfect agreement with Kai Hencken et al. calculations.

Recent paper [2, 9, 10] reports on electromagnetic production of electron-positron pair accompanied by giant dipole resonance (GDR) at RHIC for Au-Au collisions. This process is shown in figure 2 and in addition to the lepton pairs, the nuclei exchange also some photons and this may break up the nuclei. For the probability of GDR excitation in one ion we use the approximation

$$P_{GDR}(\rho) = S/\rho^2 \quad (6)$$

here

$$S = \frac{2\alpha^2 Z^3 N}{Am_N \omega} = 5.45 \times 10^{-5} Z^3 N A^{-2/3} fm^2 \quad (7)$$

where m_N is the nucleon mass, N is the neutron number, Z is the proton number and A is the mass number of the ions, respectively. More information can be found in Ref. [1, 11, 12]. We can calculate the total cross section for the electron-positron pair production accompanied by nuclear dissociation in peripheral heavy-ion collisions. Since for small values of impact parameter ρ_{min} , the probability for GDR excitation is large, we include multi-photon excitation probability as

$$P(\rho) = 1 - \exp[-P_{GDR}(\rho)]. \quad (8)$$

This equation represent the multi-photon excitation probability and restore the unitarity.

3 Results

In our Monte Carlo calculation, we have set the integral limits for the STAR experimental restrictions. We have increased the random numbers until the results are converged. We have used 10 millions

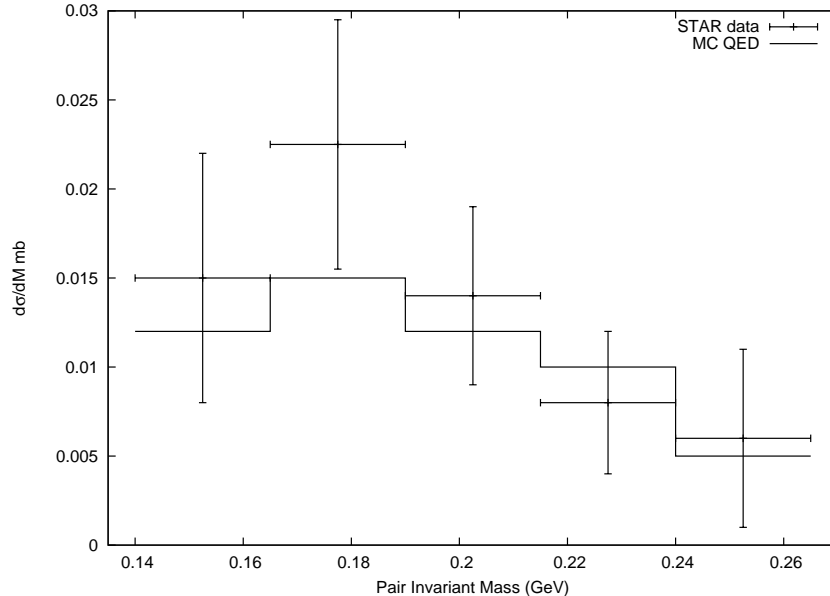


Figure 3: Differential cross section as a function of invariant pair mass, within the STAR kinematic restrictions.

Monte Carlo points for each variables. The error is less than 5 percent. We have calculated the integrated cross section for Au-Au collisions at RHIC energies with the restrictions $p_{\perp} > 65$ MeV/c, $|Y| < 1.15$. Hencken *et al.* results are 2.30 mb, 1.76 mb and 1.43 mb for the the minimum impact parameters $\rho_{min} = 13, 14, 15$ fm respectively. For the corresponding minimum impact parameters, we have obtained the tagged cross sections by Monte Carlo QED calculations and our results are 1.98 mb, 1.50 mb and 1.33 mb respectively. We have also used the same calculation with Woods-Saxon nuclear form factor. Although our results are smaller than the Hencken et al. calculations, the overall agreement is good. On the other hand, Baltz [13, 14] has calculated total cross section including the higher order QED effect and obtained a result of 1.67 mb, and it is an excellent agreement with the STAR data which is 1.65 ± 0.23 (stat) ± 0.30 (syst) mb. This could be an indication that higher-order QED effects play important role in lepton pair production in RHIC and LHC.

In Figure 3, we have compare our pair-mass distribution with the STAR experiment. The solid line shows our calculation. Our distribution is in the range of the error bars. For pair mass around 180 GeV, our result slightly underestimates the measured values. In Figure 4, we have also shown our calculation of the pair transverse momentum distribution. This distribution is also in the range of the error bars. Baltz has calculated both invariant mass distribution and pair transverse momentum distribution. He has included the higher order effects in his calculation and the result is significantly lower than the simple QED results.

4 Conclusion

We have calculated the electron-positron pair production cross section exactly by using the Monte Carlo method. In our calculation, although we have not included the higher order effects, our results are in good agreement with the Baltz calculation. Both calculations are also in good agreement with the experimental results. The calculation done by Hencken at al are also in good agreement with the experimental results, however higher than our calculations.

In future works, we are planning to include the higher order effects in our calculations. This may

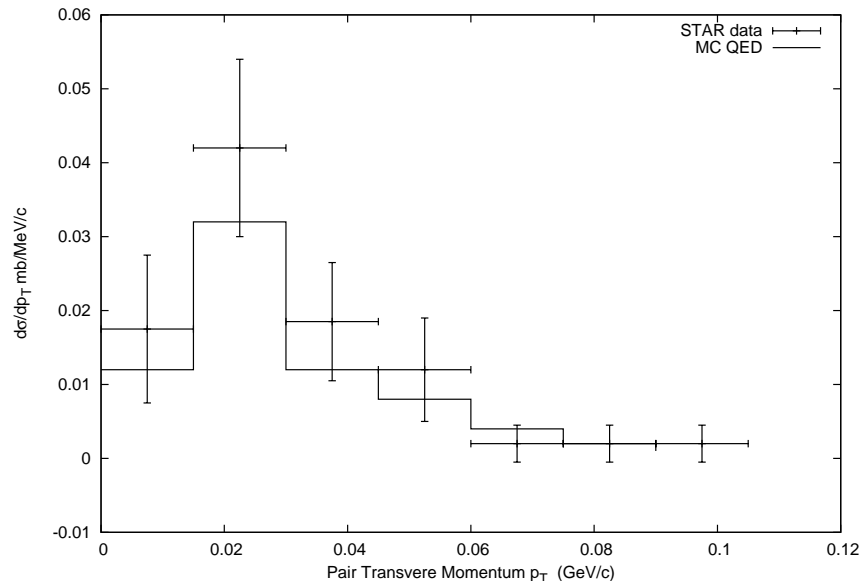


Figure 4: Differential cross section as a function of transverse momentum of the produced electrons, within the STAR kinematic restrictions.

also reduce the lepton pair production cross sections and the relevant distributions. It is important to understand the contribution of the higher-order QED effects in relativistic heavy ion collisions. RHIC produces the highest available electromagnetic fields from the heavy ions. Unfortunately, the test of QED at strong fields is not the main goal of RHIC. We need further experiments to be done at RHIC and also at LHC to answer these questions. In future experiments at RHIC and at LHC, there are some plans to improve the experimental conditions to measure the higher order effects in lepton pair productions. We may also understand the higher order Coulomb effects in these collisions.

On the other hand, GSI at Darmstadt has planned to build a new accelerator facility FAIR (Facility for Anti-proton and Ion Research) [15] with anti-proton and ion beams. Different kind of physics experiments will be performed at FAIR. One of the main goal of the FAIR project is to study "Quantum Electrodynamics QED at strong field". Although the above equations 1 and 2 are valid for the ultra-relativistic energies, when the FAIR project is completed in 2016, the available Lorentz factor γ will be up to 20 in fixed-target experiments. This could help us do experiments at intermediate relativistic energies. Studying the differential cross sections as a function of impact parameter, and bound-free pair production at this intermediate relativistic energies are some of the main goals of the FAIR.

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